MODEL EXPERIMENT ON BOOSTER CAPACITY OF JET FAN IN THE ROAD TUNNEL

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ABSTRACT

The Yamatogawa route is being constructed by Hanshin Expressway Company Limited in Osaka, Japan. The Yamatogawa route is about 9.7km in length of which 6766m is tunnel, 1541 m is lidded – trench structure.
In case of normal operation of longitudinal ventilation system, jet fans are required to control pressure of the longitudinal air flow in the tunnel. Furthermore, in case of a fire, the smoke in the vicinity of the fire point is required to be kept as close as possible to 0m/s by controlling jet fans.
A lot of destination sign boards and electric information boards are planned to be placed on the ceiling of the tunnels. It is necessary to set up each jet fan in a position where its jet flow will not affect such kind of obstruction. However, there was insufficient technical knowledge of the booster capacity of the jet fans depending on the difference of the distance between a jet fan and an obstruction, and also the distance between another jet fan.
Consequently, we examined the characteristic of booster capacity of the jet fan under various conditions by using a 1/40 scale model of the Yamatogawa tunnel.

1. INTRODUCTION

In Japan, the Meidinger's theoritical equation (eq.1) from Bernoulli's equation and momentum theorem is generally used to calculate boost pressure of jet fan.

$$\Delta Pj_{(th)} = \frac{\rho}{2} Uj^2 \cdot 2 \cdot \phi \cdot (1-\varphi) \qquad \text{(eq.1)}$$

$\Delta P_{j(th)}$: theoretical value of boost pressure of jet fan [Pa]
ρ : air density [kg/m^3]
U_j: exhaust wind velocity of jet fan [m/s]
ϕ : ratio of diameter of jet fan A_j to tunnel A_r (= A_j / A_r)
φ : ratio of wind velocity of jet fan U_j to tunnel U_r (= U_j / U_r)

In Japanese standard[1], it is regulated that the interval between jet fans and a tunnel portal or other jet fans should be 160m or more in order to apply (eq.1) when jet fans of 1,250mm in diameter are placed in a tunnel. But we should plan to install jet fans at intervals that are shorter than the standard because there are a lot of obstructions and jet fans in the Yamatogawa route. Then, to reflect the influence of these equipments in the ventilation design, we adopted the boosting coefficient Kj defined by (eq.2).

$$K_j = \frac{\Delta P_{j(ex)}}{\Delta P_{j(th)}} \qquad \text{(eq.2)}$$

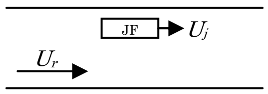
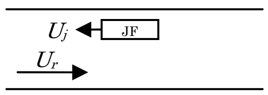
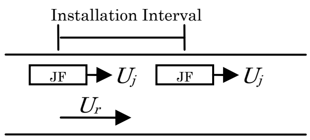
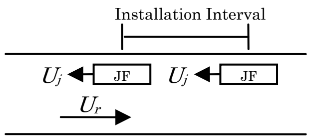
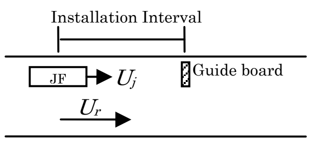
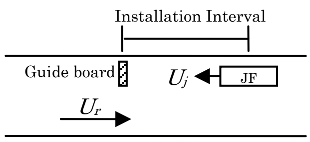
$\Delta P_{j(ex)}$: actual value of boost pressure of jet fan [Pa]

Kj is a ratio of an actual to a theoretical boost pressure, that is, a value to correct the power of the jet fan under each condition. We measured the value of Kj with tunnel model under various conditions, and determined this value as a standard of the ventilation design in Hanshin Expressway.

2. EXPERIMENT CASES

Jet fans in Yamatogawa route is used to control pressure in the tunnel, and also flow of smoke in case of fire, so that it is important for an accurate ventilation design to understand the influence of the air flow in the tunnel on booster power of jet fan. Moreover, as noted before, it is difficult to leave plenty of room between jet fans and other equipments in the Yamatogawa route, hence, we should also get to know the relationship of the interval between the jet fan and the other equipments with the boosting coefficient. Consequently, for the purpose of clarifying those relationships, we measured the boosting coefficient with model experiment when the jet fans were installed in a section, when in two sections at various intervals, and when the jet fans and the sign boards were installed at various intervals, as shown in Table1.

Table 1 Experiment cases

Cases	Types	Number of Jet-fans (bore diameter)	Jet-fan flow direction	U_r [m/s]	U_j [m/s]	Installation Interval* [m]
CASE1		2 (1250mm*)	Normal	4,6,8,10,12	35	-
				4,6,8,10,12	30	-
				4,6,8	20	-
			Reverse	4,6,8,10,12	35	-
				4,6,8,10,12	30	-
				4,6,8	20	-
CASE2		4 (1250mm*)	Normal	4,8	35	60,80,100,120
				4,8	30	60,80,100,120
				4,8	25	60,80,100,120
			Reverse	4,8	35	60
				4,8	30	60,80,100,120
CASE3		2 (1250mm*)	Normal	4,8	35	60,80,100,120
				4,8	30	60,80,100,120
				4,8	25	60,80,100,120
			Reverse	4,8	35	60
				4,8	30	60

*:Full-scale conversion

3. OVERVIEW OF EXPERIMENTAL EQUIPMENTS

The diagrammatic illustration of the experimental apparatus used by this experiment and the cross section of the tunnel model are shown in Figure 1. The experimental apparatus consists of a 1/40 scale model made of acrylic, jet fans, sign boards, a blower for jet fan, and a flow quantity measurement system. We simulated that the jet fans of 1,250mm in diameter and the sign boards of 7.5m^2 are placed on the ceiling of the shield tunnel whose cross section is equivalent to 74m^2. The jet fans and the sign boards could be removed from the tunnel model freely, in order to examine the boosting coefficient of the jet fan depending on the difference of the distance between the jet fan and the sign board, and also the distance between another jet fan. Valves, pressure gauges, and data logger are installed to the model, and we measured static pressure distribution with these devices.

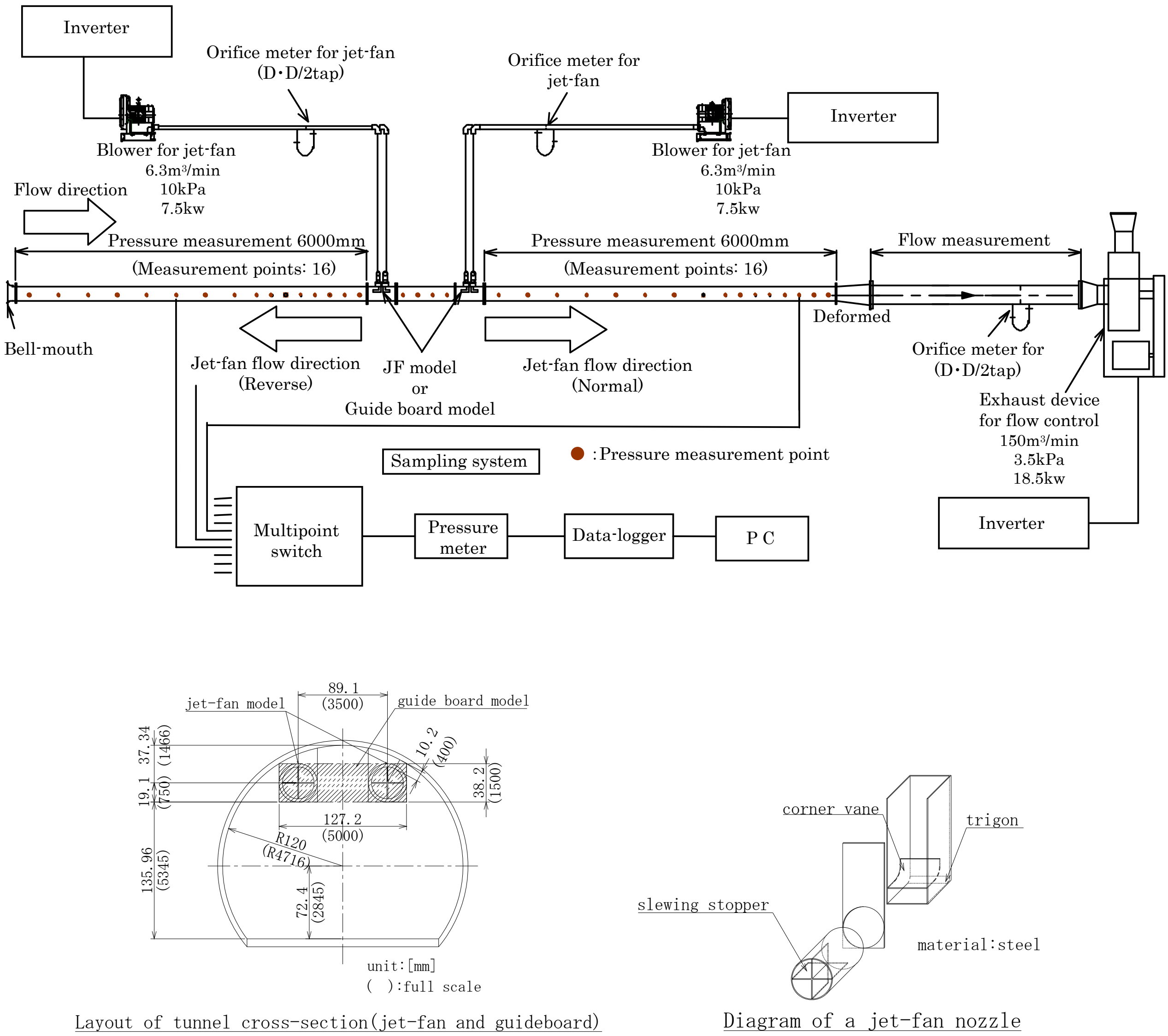


Figure 1 Scheme of experimental equipment

4. DEFINITION OF BOOSTING COEFFICIENT

This chapter explains the idea of the boosting coefficient of the jet fan in each experiment case. The diagrammatic illustration of the static pressure distribution in the tunnel in each experiment case is shown in Figure 2.

4-1 CASE 1

The actual booster pressure ΔPj(ex) of two jet fans placed in the cross section 1 is shown by I in Figure 2, and obtained by measuring the static pressure between upstream and downstream of the jet fans. Therefore, the boosting coefficient Kj in this case is shown by (eq.3) with theoretical pressure ΔPj(th).

$$K_j = \frac{\Delta P_{j(ex)}}{2\Delta P_{j(th)}} = \frac{\Delta P_{j(ex)}}{\rho U_j^{\,2} \cdot 2 \cdot \phi \cdot (1-\varphi)_j} \qquad \text{(eq.3)}$$

4-2 CASE 2

In this case, four jet fans are installed in two cross sections. The actual boost pressure ΔPj(ex) of two jet fans placed in cross section 1 is shown by II in Figure 2, and obtained by measuring the static pressure between upstream and downstream of the jet fans, as well as case1. Consequently, the boosting coefficient Kj in this case is shown by (eq.4) with theoretical pressure ΔPj(th).

$$K_j = \frac{\Delta P_{j(ex)}}{4\Delta P_{j(th)}} = \frac{\Delta P_{j(ex)}}{2\rho U_j^{\,2} \cdot 2 \cdot \phi \cdot (1-\varphi)_j} \qquad \text{(eq.4)}$$

4-3 CASE 3

It is difficult to measure actual boost pressure of jet fans ΔPj(ex) under the condition of this case, so we calculated ΔPj(ex) by adding a pressure loss of the sign board ΔPs(ex) to a difference of the static pressure in the tunnel in the section from the jet fan upstream to the sign board downstream ΔPj(ex)'(ΔPj(ex)'is shown by III in Figure 2). The pressure loss ΔPs(ex) is shown by (eq.5) by using a pressure loss coefficient ζs(ex).

$$\Delta P_{s(ex)} = \zeta_{s(ex)} \frac{\rho}{2} Ur^2 \qquad \text{(eq.5)}$$

Therefore, the boosting coefficient Kj in this case is shown by (eq.6) with theoretical pressure ΔPj(th).

$$K_j = \frac{\Delta P_{j(ex)}}{2\Delta P_{j(th)}} = \frac{\Delta P_{j(ex)}' + \Delta P_{s(ex)}}{\rho U_j^{\,2} \cdot 2 \cdot \phi \cdot (1-\varphi)_j} = \frac{\Delta P_{j(ex)}' + \zeta_{s(ex)} \frac{\rho}{2} Ur^2}{\rho U_j^{\,2} \cdot 2 \cdot \phi \cdot (1-\varphi)_j} \qquad \text{(eq.6)}$$

At this experiment case, the pressure loss coefficient ζs(ex) of the sign board should be measured with preliminary experiment in order to calculate the pressure loss of the direction board

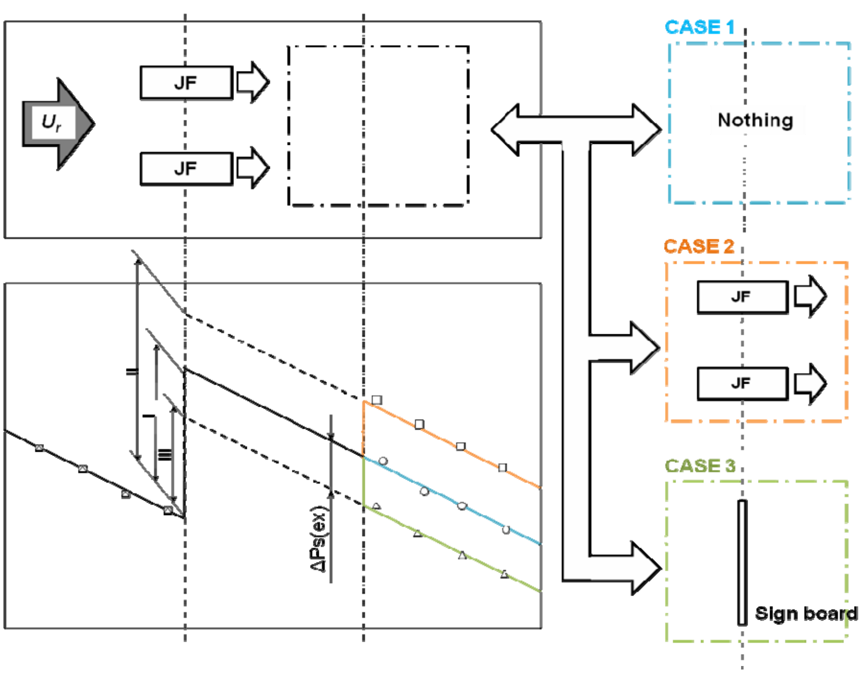


Figure 2 Schematic view of pressure distribution

5. RESULT OF EXPERIMENT

5-1 Preliminary experiment

5-1-1 Friction factor of tunnel λ

In this experiment, the boost pressure of the jet fan is calculated with the difference of the static pressure between upstream and downstream of the jet fans. The static pressure in the tunnel changes linearly in the part where the jet fans or the sign boards have no effect on the air flow, and the gradient in this part depend on the friction factor λ Therefore, we conducted verification experiment for the friction factor λ of the tunnel model, and decided the gradient of static pressure distribution. In general, a friction loss ΔPr in the section of L(m) is defined by (eq.7).

$$\Delta P_r = \lambda \frac{L}{Dr} \frac{\rho}{2} Ur^2 \qquad \text{(eq.7)}$$

λ: friction factor [-]
Dr: diameter of tunnel [m]
ρ: air density [kg/m^3]
Ur: wind velocity in the tunnel [m/s]

The friction factor λ is shown by (eq.8) by using (eq.7)

$$\lambda = \frac{2\Delta \mathrm{Pr} \cdot Dr}{\rho \cdot L \cdot Ur^2} \qquad \text{(eq.8)}$$

The friction factor λ depends on Reynolds number Re [-] defined by (eq.9), we experimented on 10 cases of different Reynolds numbers.

$$\mathrm{Re} = \frac{Ur \cdot Dr}{\nu} \qquad \text{(eq.9)}$$

ν : kinetic viscosity [m^2/s]

A relationship between Reynolds number Re and friction factor λ, which is calculated by (eq.8) with static pressure, wind velocity, and condition of air in tunnel, is shown by Figure 3. Though the friction factor λ becomes small as Reynolds number Re grows, it changes significantly in area where Reynolds number Re is small. In this experiment, friction factor in each condition is obtained by Figure 3.

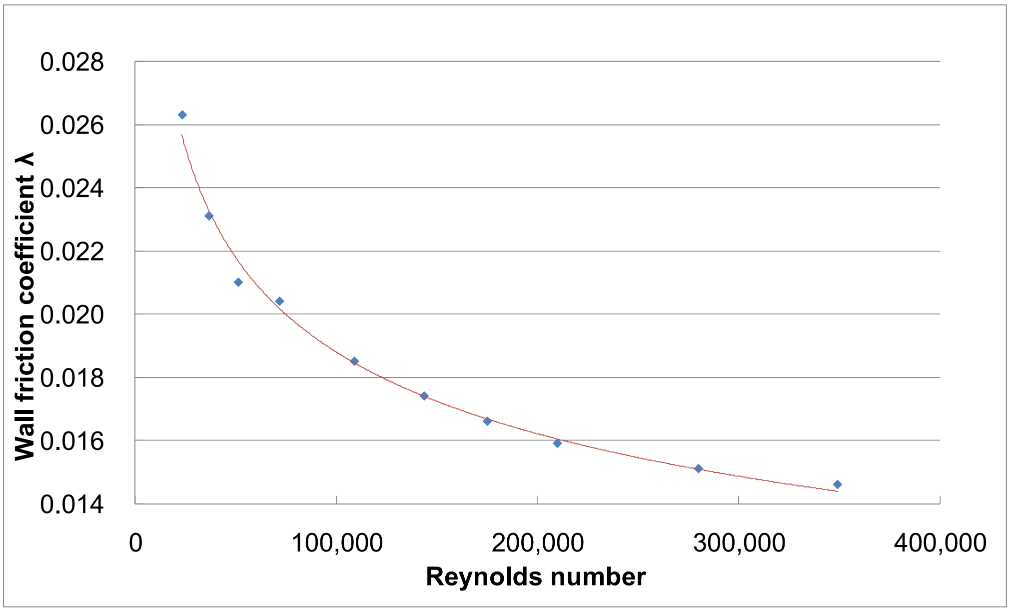


Figure 3 Relationship between the Re and λ

5-1-2 Drag coefficient of sign board ζs(ex)

It is necessary to understand the characteristic of the pressure loss coefficient of the sign board ζs(ex) to calculate the boosting coefficient Kj by (eq.6) in experiment case 3. The relationship between the pressure loss coefficient ζs(ex), the Reynolds number Re and the direction board is examined by experiment. The pressure loss coefficient of the sign board ζs(ex) is shown by (eq.10) from (eq.5).

$$\zeta_{s(ex)} = \frac{\Delta P_{s(ex)}}{\frac{\rho}{2} Ur^2} \qquad \text{(eq.10)}$$

The Relationship between the Reynolds number Re and the pressure loss coefficient of the sign board ζs(ex), which is calculated by (eq.10) with static pressure, wind velocity, and condition of air in tunnel, is shown by Figure 4. The pressure loss coefficient of the sign board changes less as the Reynolds number Re grows. The pressure loss coefficient in each condition is obtained by Figure 4.

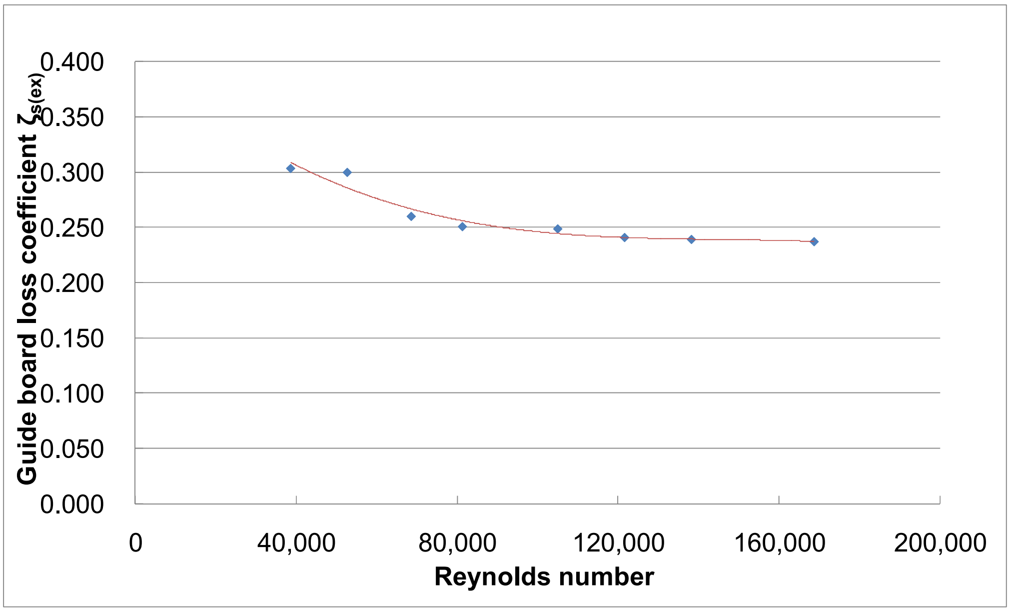


Figure 4 Relationship between the Re and $\zeta_{s(ex)}$

5-2 Result of experiment

5-2-1 Relationship between wind velocity in tunnel Ur and boosting coefficient Kj (Experiment 1)

Figure 5 is a graph showing the relationship between the wind velocity Ur (JF normal rotation and reversal) and the boosting coefficient Kj, and Figure 6 shows between wind velocity ratio Ur / Uj (JF normal rotation and reversal) and Kj. Knowledge as follows is gleaned from these graphs.

a) When jet fans operate in normal rotation, the wind velocity Ur have a great influence on the boosting coefficient Kj, and Kj becomes small as the wind velocity in tunnel grows.
b) When the wind velocity ratio Ur / Uj in the tunnel is the same, the boosting coefficient Kj reaches almost the same value regardless of exhaust wind velocity of jet fan Uj.
c) When the jet fans operate in reversal rotation, the value of Kj is approximately 0.95 regardless of wind velocity ratio Ur / Uj.

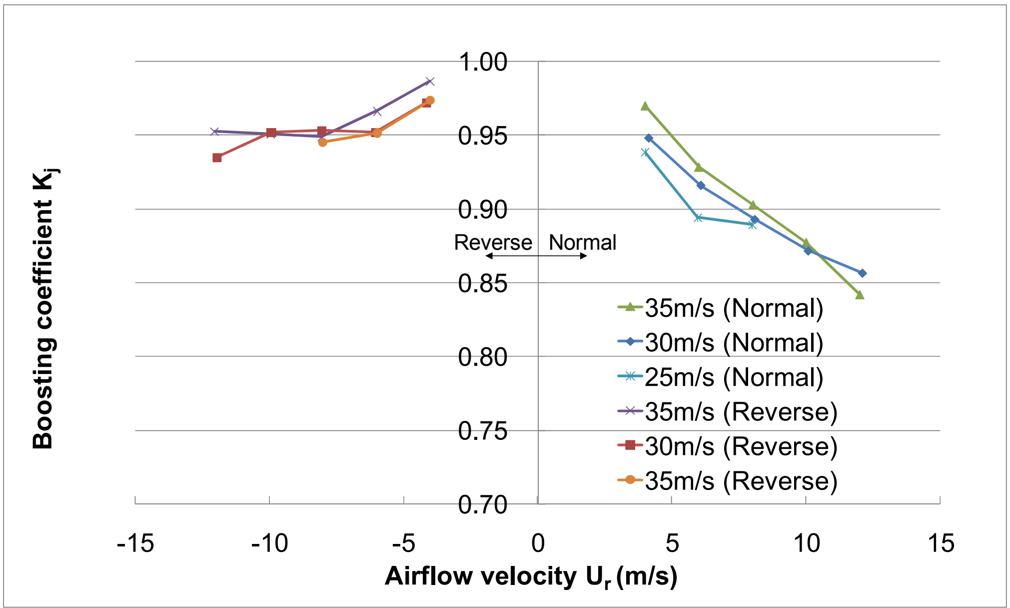


Figure 5 Relationship between the U_r and K_j (CASE1)

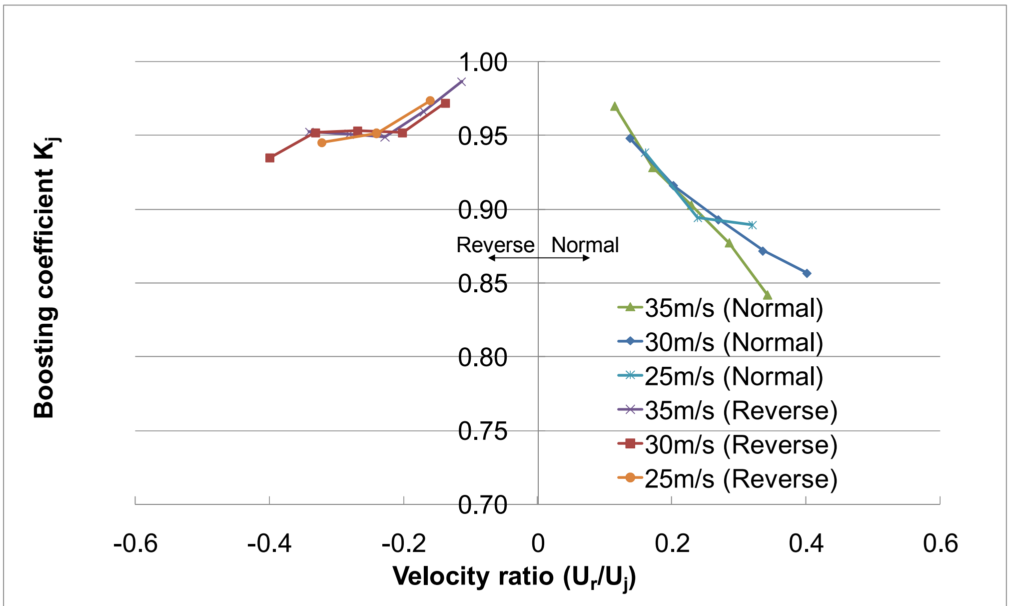
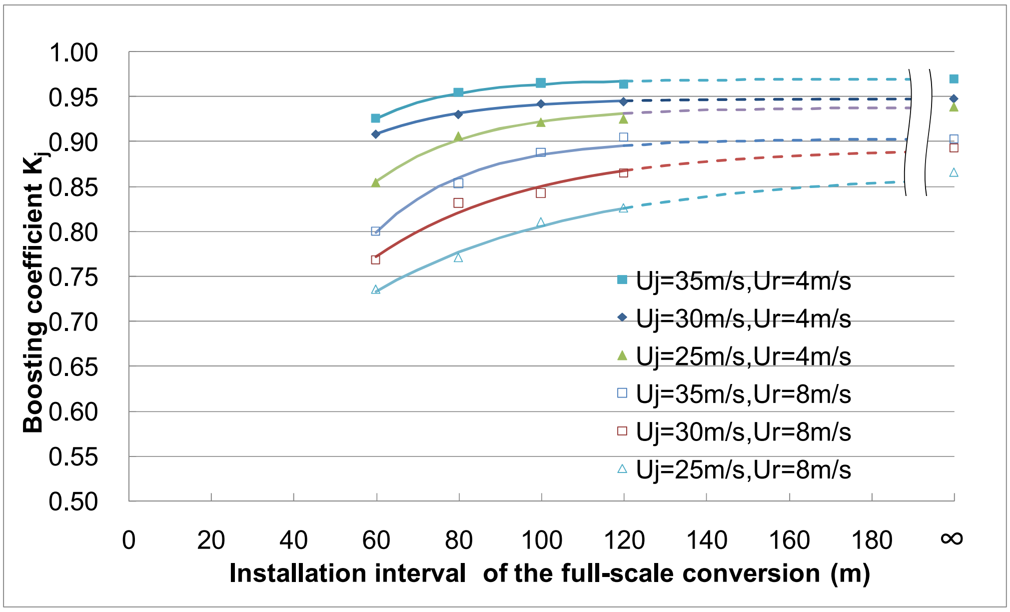


Figure 6 Relationship between the Velocity ratio Ur / Uj and K_j (CASE1)

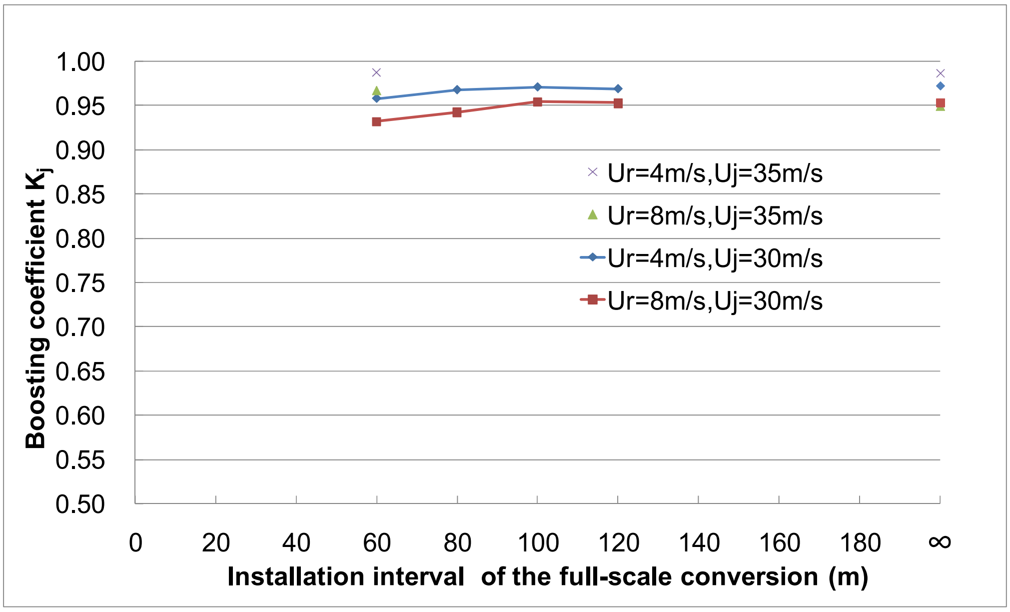
5-2-2 Relationship between interval of jet fans and boosting coefficient Kj (Experiment 2)

The Relationship between the interval of the jet fans and the boosting coefficient Kj, which was obtained by experiments, is shown by Figure 7. The value indicated in ∞ of a horizontal axis is a result of experiment 1. Knowledge as follows is gleaned from these graphs.

a) When jet fans operate in normal rotation, the shorter the interval of jet fans become, the less the value of Kj is. And the less exhaust wind velocity of jet fan Uj become, the less the value of Kj is.
b) When interval of jet fans become 100m or more, the value of Kj becomes almost equal to that in case of single installation.
c) When jet fans operate in reversal rotation, the shorter the interval jet fans become, the less the value of Kj is, but the amount of the change is small enough compared with the case of normal rotation, and the influence of the interval of the jet fans on Kj is small. And the boosting coefficient Kj is almost the same value regardless of exhaust wind velocity of jet fan Uj.



a) Normal flow direction(Jet-fun)



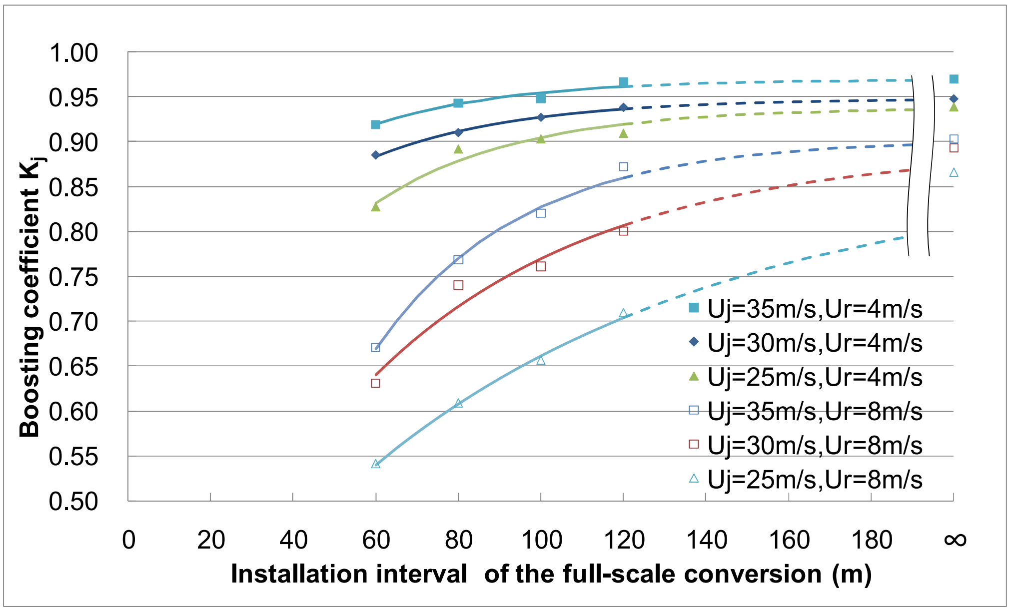
b) Reverse flow direction(Jet-fun)

Figure 7 Relationship between the installation interval and K_j(CASE2)

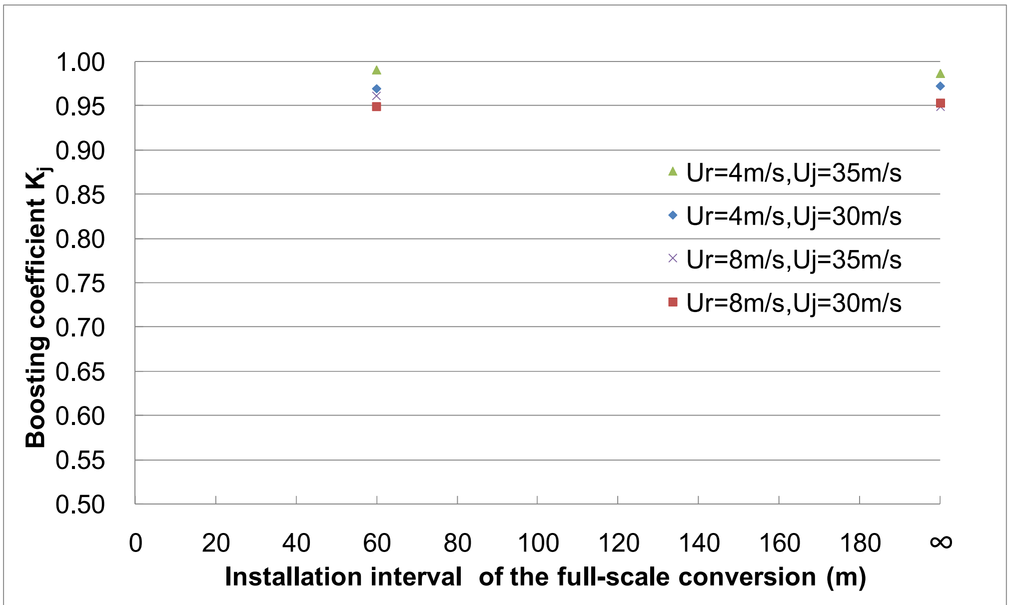
5-2-3 Relationship of interval between jet fan and sign board with boosting coefficient Kj (Experiment 3)

Relation of interval between jet fan and sign board with boosting coefficient Kj, which was obtained by experiments, is shown by Figure 8. The value indicated in ∞ of a horizontal axis is a result of experiment 1. Knowledge as follows is gleaned from these graphs.

a) When the jet fans operate in the normal rotation, the shorter the interval between the jet fan and the sign board become, the less the value of Kj is.
b) When jet fans operate in reversal rotation, the amount of the change is small enough compared with the case of the normal rotation, and influence of interval of jet fans on Kj is small.
c) The sign board has a bigger influence on the boosting coefficient Kj than other jet fans placed on another section.



a) Normal flow direction(Jet-fun)



b) Reverse flow direction(Jet-fan)

Figure 8 Relationship between the installation interval and K_j(CASE3)

6. CONCLUSIONS

With the goal of clarifying the effect of various conditions on the boost pressure of the jet fans, we measured the boosting coefficient with the model experiment when the jet fans were installed in a section, when in two sections at various intervals, and when the jet fans and the sign boards were installed at the various intervals. As a result of the model experiment, the booster capacities in each case are shown in Table 2.

Table 2 Relationship between Kj and each contditions
(exhaust wind velocity of jet fan Uj : 30, 35 m/s)

Jet fans installed in a section(case 1)

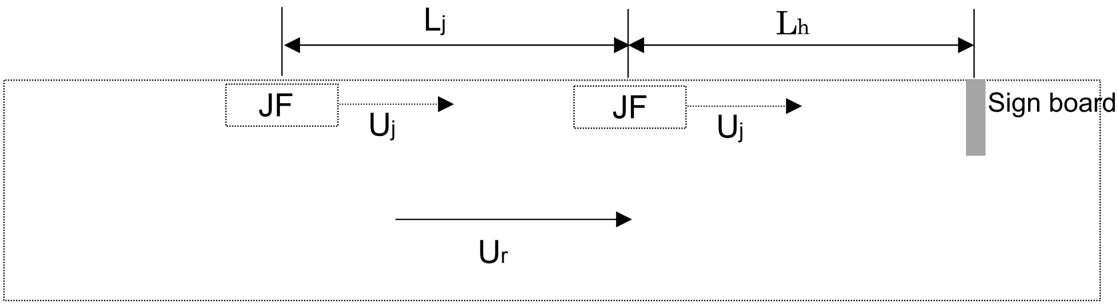
Ur(m/s)	Kj
0<Ur≦4	0.9
4<Ur≦8	0.85
-4<Ur≦0	0.95
-8<Ur≦-4	0.95

Jet fans installed in 2 sections(case 2)

Ur(m/s)	Lj(m)	Kj
0<Ur≦4	60	0.9
	80	0.9
	100	0.9
	120	0.9
4<Ur≦8	60	0.75
	80	0.8
	100	0.85
	120	0.85
-4<Ur≦0	60	0.95
	80	0.95
	100	0.95
	120	0.95
-8<Ur≦-4	60	0.9
	80	0.9
	100	0.95
	120	0.95

Jet fans and sign board installed in 2 sections(case 3)

Ur(m/s)	Lh(m)	Kj
0<Ur≦4	60	0.85
	80	0.9
	100	0.9
	120	0.9
4<Ur≦8	60	0.65
	80	0.7
	100	0.75
	120	0.8
-4<Ur≦0	60	0.95
	80	0.95
	100	0.95
	120	0.95
-8<Ur≦-4	60	0.95
	80	0.95
	100	0.95
	120	0.95



The following contents became clear from the above-mentioned results of this experiment.

a) When jet fans operate in normal rotation, the boosting coefficient Kj is 0.9 in the range of 4m/s or less of the wind velocity in the tunnel regardless of the presence of the installation of the other jet fans or sign boards.
b) When jet fans operate in reversal rotation, Kj is 0.95 except that interval between the jet fans is short.
c) As a general trend, the sign board has a big influence on the boosting coefficient Kj than other jet fans placed on another section. So if plenty of room between jet fans and other equipments cannot be left, it is effective to design the ventilation, saving the distance of the sign board and the jet fan by priority.

REFERENCES

[1] Technical standard for road tunnels (ventilation) and explanation, Japan Road Association (2008) (in Japanese)
[2] A. Mizuno, T. Azuma, A. Ichikawa, T. Kano: Appropriate JF installation interval obtained by booster capacity measurements, 10th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels, BHR Group, pp. 431-446 (Boston, U.S.A., Nov. 2000)